DESIGN OF A LASER RF MODULATION PHASE SENSITIVE SCHEME FOR SENSING AND DECODING MULTIMODAL VIBRATION IN LARGE COMPOSITE SPACE STRUCTURES

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INTRODUCTION

Current designs for large light-weight space structures prompt the need for enhanced damping of the structural system to improve system performance and/or simplify the controls designs. Enhancement of passive damping with local active damping is very desirable. Development of embedded sensors, actuators, and signal processing systems would provide local control superior to passive damping techniques.

A structural strain sensor design that is an outgrowth of a technique first demonstrated by Rogowski, et al [1] is described. A high speed diode laser is modulated by a stable oscillator chosen for its stability and low phase noise. The laser output is split into a multiplicity of fibers through a coupler - in this case four. Each fiber is bonded to the surface of the composite tube, symmetrically about and parallel to the axis. Each fiber terminates in a photodetector, which is capacitively coupled to one input port of a double balanced mixer. The rf source signal is split, as was the optical signal, and is fed to each of the double balanced mixers. Each of the rf branches is passed through a phase delay compensator before entering the modulators to establish a phase difference between the rf source and all optical signals of 90 degrees so that all mixer outputs are zero when the structure is straight and quiescent. As described in the system developed by Rogowski, et al [1], the mixer outputs are DC voltages proportional to the strain induced phase shifts. These signals modulate simultaneously at the frequencies of the vibrational modes of the structure (e.g., longitudinal, bending and torsional). Proper linear combinations of the signals from each mixer must be taken to separate the temporal signals corresponding to each mode of vibration. These orthogonalized signals can be appropriately amplified and directed to structural actuators which control the vibrational dynamics.

The concept developed by Rogowski, et al [1], is shown in Figure 1. In its original implementation, an optical fiber was bonded to one side of a multi-ply graphite epoxy composite beam cantilever mounted and free to oscillate in the vertical direction in the fundamental cantilever mode. The fiber formed an optical delay line through which was transmitted a laser beam whose optical intensity was sinusoidally modulated at 300 MHz. The phase of the transmitted signal was compared to that of the frequency source. A stretching/contracting of the fiber is induced by virtue of longitudinal tension/compression of the two surfaces of the beam as it bends. A stretching results in an increase in the phase delay through the fiber. A phase locked loop was established by taking the DC error signal from a double balanced mixer to adjust the oscillator frequency. A counter measures the change in frequency as the beam flexes. Rogowski [1] reported a typical response showing a decaying sinusoidal oscillation with a period corresponding to the fundamental mode of oscillation. Higher order modes of vibration can be produced by appropriate excitation. These can be detected by Fourier decomposition of the observed signal.

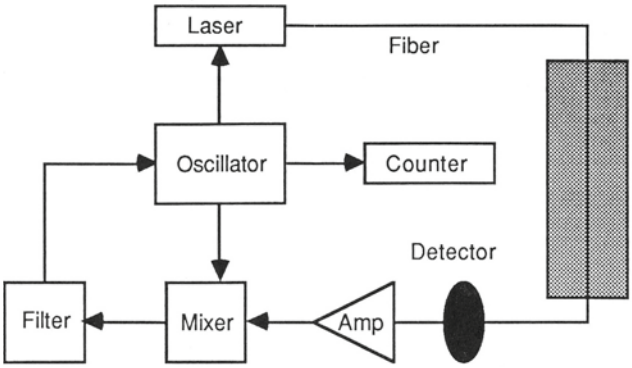

Figure 1. Fiber optic sensor developed by Rogowski, et al [1]

MULTIMODAL SENSOR DESIGN

Use of this method would require one laser and varactor controlled oscillator (VCO) rf source for each sensing fiber. High performance lasers and detectors, capable of high frequency operation, are expensive. The design proposed below makes use of the same phase comparison technique, but takes advantage of fiber optic beam splitting to sense more than one elastic mode of the structure, and provides for a simple and clean method of damping multiple excitations simultaneously and orthogonally.

Figure 2 illustrates the sensor system. A high performance laser with a bandwidth greater than 1 Ghz is chosen as the optical source (Ortel). It is modulated by a stable oscillator that is not part of a phase locked loop, and is thus chosen for its stability rather than tuning bandwidth. It will therefore contribute less phase noise to the signals.

The laser output is split into a multiplicity of fibers through a coupler - in this case four. The link is a rectangular cross-section hollow tube for the sake of clarity in the illustration, but the discussion follows similarly for cylindrical tubes. Thus, each fiber is laid on the (inner or outer) surface of the beam, parallel to the beam axis, bonded to each planar face.

Each fiber terminates in a photodetector, which is capacitively coupled to one input port of a double balanced mixer. The rf source signal is split, in much the same way that the optical signal was, and is fed to each of the double balanced mixers. Each of the rf branches is passed through a phase delay compensator before entering the modulators so that the nominal phase differences between the rf source and all optical signals are each 90 degrees when the structure is straight and quiescent, so that all mixer outputs are zero. As described in the system developed by Rogowski, et al [1], the mixer outputs are DC voltages proportional to the strain induced phase shifts. These DC signals, which will modulate at the frequency of the vibrational modes of the structure, are used to drive the actuators that dampen the dynamic modes of the structure.

The control system bandwidth is many orders of magnitude greater than the low frequency spectra (a few Hertz) expected for the structural vibration modes of any significant amplitude.

The vibration controller system is attractive for its simplicity of design: It is analog and requires no digital microprocessor. Its subsystems consist of the fiber optic sensor system, signal conditioning/amplification electronics and the actuators. The electronics consists of a diode laser, detector, radio frequency (rf) source, double balanced mixers, amplifiers and power supplies for the active components. The sensor system is described first.

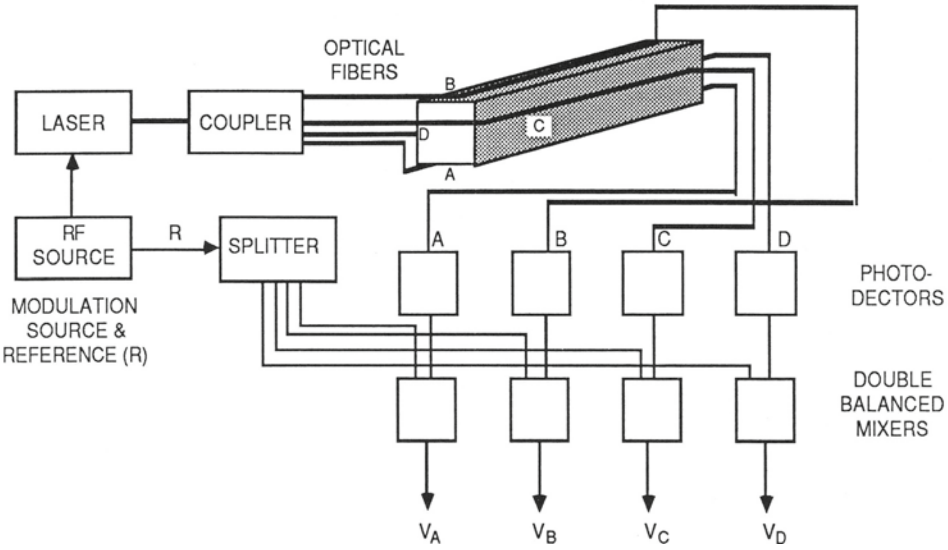

Figure 2. RF Modulated Fiber Optic Sensor System

Consider the information obtainable from two fibers on opposite sides of the beam - in this case fibers A and B in Figure 2. Should the beam experience pure tension or compression, the voltages V_A and V_B will be identical and of the same sign, so that their difference is zero. If the beam experiences pure flexure so that the neutral axis neither compresses nor extends, the voltages V_A and V_B will be identical in magnitude and of opposite sign, so that summing them will yield zero. Taking their difference, as in an operational amplifier, produces a signal corresponding to pure bending. Adding the two voltages in an operational amplifier produces a signal corresponding to pure longitudinal vibration. It is this process of taking linear combinations of simple DC voltages that is exploited in generating output signals that drive opposing surfaces of the structure for simultaneously occurring bending and longitudinal vibrations.

CONTROL OF FLEXIBLE STRUCTURES

To control the vibration of the flexible structure, a linear feedback system would be implemented. In a decoupled control system, the corrective command sent to an actuator is based only on the strain local to the actuator. That is, an actuator is commanded without consideration of its effect on the remote portions of the link. This results in a set of simple, decoupled control laws, given by

$$U_i = - B_i de_i/dt - K_i e_i \qquad (1)$$

where U_i is the commanded voltage to actuator i, e_i is the strain measured at actuator i, and B_i and K_i are constants. Here B_i represents an electronically added damper for damping the link vibration local to actuator i, and K_i represents an electronically added spring for counteracting the local deformation. Note that this control law corresponds to a PD (proportional plus derivative) controller. An integral term may also be added to eliminate any steady state deformation , such as may be caused by warp or damage.

A flexible structure is a continuous medium that requires partial differential equations to describe its full dynamics. The structure will be approximated using a finite element model to generate a set of ordinary differential equations. The simplified finite-dimensional model will permit the application of conventional control analysis techniques. Using this model, the strain interaction between different portions of the structure can be considered, and the

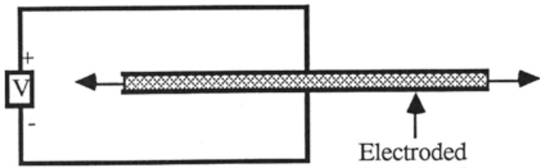

Figure 3. Shear behavior of a piezoelectric to an applied voltage

control command to an actuator will be based on the entire set of strain measurements. The control law for the coupled control system will be of the form

$$U = -B\, de/dt - K e \qquad (2)$$

where $U = [U_1\ U_2 \ldots U_n]$, B and K are nxn matrices.

EMBEDDED ACTUATOR TECHNOLOGY

This information can be used in a simple way: Through the direct amplification of the analog error signal to drive piezo-ceramics to actively damp vibrations.

A plate of piezoelectric ceramic poled in the shear excitation mode direction (Figure 3) responds to an applied voltage as

$$S_1 = d_{31} * V_3/t \qquad (3)$$

where S_1 is the induced static strain in the 1-direction when subjected to a voltage in the 3-direction, and t is the thickness of the plate (3-direction). PZT poled ceramic has a typical static piezoelectric strain constant $d_{31} = 110 * 10^{-12}$ m/volt.

A free ceramic plate 110 microns thick would exhibit 1 microstrain per applied volt. This is a measure of the strain that can be absorbed from the structure during each cycle of vibration.

By embedding a plurality of such elements in a structure, as in Figure 4, we may define an actuator/controller system that can subdue vibration in flexible composites.

Fabrication of Piezoceramic Actuators

Embedment of piezoceramic actuators in graphite/epoxy composite structures must take into account the conductivity of the graphite, which will lead to short circuiting the actuators. Fortunately, Crawley et al [2] have investigated the material and electrical considerations in accomplishing embedment. The piezoceramics are available as thin wafers (7.5 mils thick) with metalized surfaces. However, more complex shapes are feasible. The wafer element must be properly encapsulated in an insulating layer. Crawley used Kapton film. The film must be thin and bonded to the ceramic with an extremely thin layer of adhesive to insure proper transfer of the strain field from the ceramic to the composite structure. Acrylic epoxies have been found suitable and can cure during the regular cycle of material processing.

Placement of Actuators on the Structure

As has been pointed out by Crawley [2], the sensible location for placement of the actuators is away from strain nodal points of any vibrational modes. For cantilever mounted beams, this means mounting close to the root for efficient coupling to the fundamental mode. The next higher mode has a standing node, and actuators must be located away from this point, preferably at points of maximum strain.

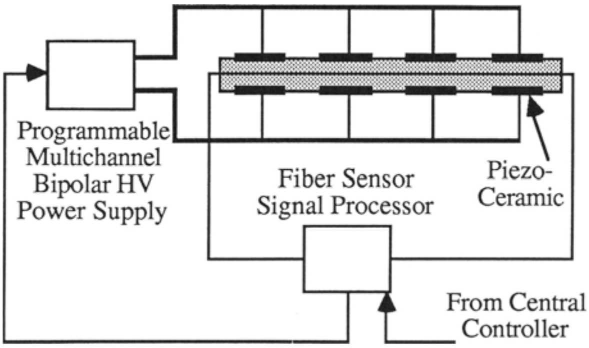

Figure 4. Configuration of actuators on a flexible structure

Any single structural element would be a component of a much larger system, e.g., the Space Station or a space based radar or laser platform. Thus, the control dynamics is that of the larger structure and not that of the individual links. In that regime of modeling and control, each link will display simple deformation in the frequency domain well below the fundamental bending resonance of the single link. Figure 5 illustrates the concept. The wavelength of any vibrational mode that is likely to exist in the larger structure is more than twice the length of the individual link. Thus, each link can be treated as deforming approximately uniformly over nearly its entire length, i.e., the in-plane strain is nearly constant along the length of the link. This is equivalent to a constant radius of curvature. This quadratic approximation will be valid if the structure is large relative to the link length (greater than 4 or 5:1) and the modal amplitudes do not exceed certain limits.

In the context of the foregoing discussion, placement of the actuators symmetrically about the center of the link, and nearly uniformly along the length will be an efficient configuration and will correspond to collocation with the fiber optic sensor.

Choice of Piezoelectric Actuators

The choice of piezoceramic material is dictated by the requirements that (1) actuators have mechanical stiffness comparable to or greater than the host material, and (2) if piezoelectric actuation is chosen, then ferroelectric polarization must not be affected by the cure process. Piezoelectricity in ferroelectric materials is destroyed by depoling if the material is raised above the ferroelectric Curie temperature. If the material is to be embedded in the composite prior to curing, then the actuator must be chosen from material with a Curie point higher than the maximum temperature occurring during cure. This restricts the choice to a piezoceramic with a depoling temperature typically higher than 350 degrees F. Crawley, et al, [2] selected a lead zirconate titanate ceramic (PZT G-1195, Piezoelectric Products, Inc.) with a Curie temperature of 360° C.

Other materials are available: piezo polymers and co-polymers, for example. Burke and Hubbard [3] have described the use of polyvinylidene fluoride (PVDF) as active damping actuators. These materials, however, have much lower Curie temperatures (100° C) and must be bonded to the structure after its fabrication. In addition, polymers have far less stiffness and do not have a good mechanical impedance match to cured composites or metallic structures. Magnetostrictive actuators are also a possibility. A magnetostrictive element, serving as the core of a spiral wound inductor, will undergo strain in response to the induced magnetic field. The significant electrical current requirements and relatively higher electrical losses of such devices are detracting features of this approach.

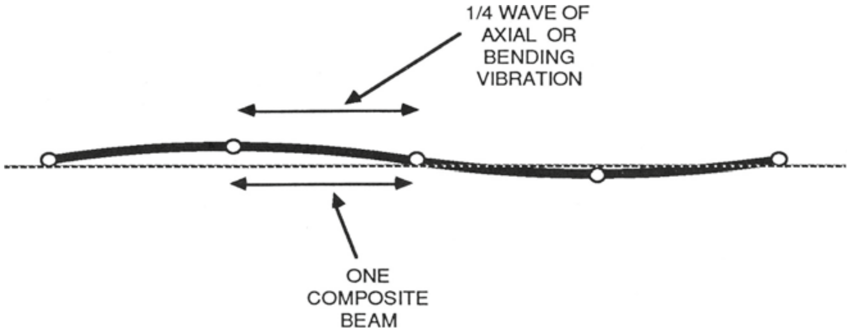

Figure 5. Relationship between an individual beam and structural dynamics.

SUMMARY

A fiber optic sensor system based on the detection of phase delay detected in the rf modulation envelope of an optical signal injected into a multiplicity of optical fibers that are embedded within a composite structure has been described. A control system is suggested which is based on the detection of phase delays occurring in several fibers embedded in the structure in a manner that permits the simultaneous extraction of longitudinal and bending strain data, is entirely analog in design, and applies output signals to an array of appropriately placed piezoceramic actuators in order to damp bending and longitudinal vibrations simultaneously. With additional placement of sensors and actuators torsional bending may be detected and controlled as well. Based on mechanical, fabrication and electrical considerations, preliminary analysis of possible actuator technologies confirms that piezoelectric ceramic elements is promising and sensible.

ACKNOWLEDGEMENTS

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